Novel Anatomic Concepts in Magnetic Resonance Imaging of the Rotator Cuff Tendons and the Footprint

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KEYWORDS

• Rotator cuff • Footprint • Anatomy • MR imaging

The anatomic and histologic descriptions of the rotator cuff tendons and footprints are continuously evolving, and new discoveries have led to novel concepts in our understanding of rotator cuff tendon pathology. These concepts may be translated into the analysis of these footprints with imaging methods, particularly magnetic resonance (MR) imaging.

FOOTPRINT OF THE SUPRASPINATUS, INFRASPINATUS, AND TERES MINOR TENDONS

Understanding the osseous anatomy of the humeral head is an important requisite for describing the rotator cuff tendon insertions. The classic anatomy of the greater tuberosity of the proximal humerus describes 3 impressions or facets, which have often been designated as superior, middle, and inferior facets or, alternatively, as horizontal, oblique, and vertical facets (**Fig. 1**). As in previous anatomic studies and traditional descriptions, these facets receive the insertional fibers of the supraspinatus, infraspinatus, and teres minor tendons, respectively.[1–4] Some of the most extensive gross anatomic and histologic work was performed by Clark and Harryman.[5] They found that the rotator cuff tendons fused as one inseparable structure at or near their insertions on the tuberosities of the humerus. The superficial fibers of the tendons generally maintained a parallel relationship with their respective muscle bellies. The supraspinatus and infraspinatus tendons were found to fuse into one inseparable tendon approximately 15 mm from their greater tuberosity insertions. These investigators depicted an interweaving of the supraspinatus and infraspinatus tendons as they coursed toward the greater tuberosity, with some of the anterior fibers of the infraspinatus tendon attaching far anteriorly (**Fig. 2**). However, the actual anterior extent of these fibers was never elucidated.

In addition to their gross descriptions of the rotator cuff tendons, Clark and Harryman[5] described 5 distinct histologic layers of the supraspinatus and infraspinatus tendons: (1) most superiorly, a thin (1 mm in thickness) superficial layer comprising fibers of the coracohumeral ligament; (2) a thicker layer (3–5 mm) of parallel tendon fibers; (3) a deeper layer (3 mm) comprising tendon fibers without uniform orientation, crossing over one another at 45° angles; (4) a layer of loose connective tissue with thick collagen bands, which merge with the coracohumeral

The authors have nothing to disclose.
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Magn Reson Imaging Clin N Am 20 (2012) 163–172
doi:10.1016/j.mric.2012.01.006

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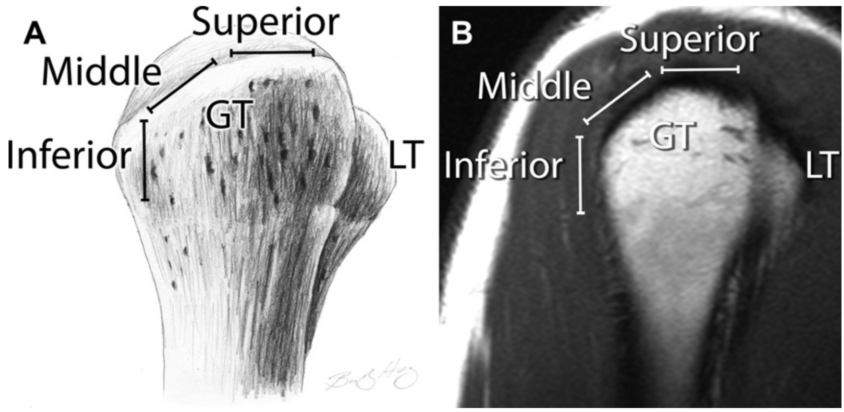

Fig. 1. (*A*) Osseous anatomy of the proximal humerus as viewed from its lateral aspect: 2 bony prominences designated as the greater tuberosity (GT), receiving the insertions of the supraspinatus, infraspinatus, and teres minor tendons, and the lesser tuberosity (LT), receiving the insertion of the subscapularis tendon. The 3 facets of the GT include the superior, middle, and inferior facets, also referred to as the horizontal, oblique, and vertical facets. (*B*) Corresponding oblique sagittal T1-weighted MR image (repetition time [TR]/echo time [TE] = 551/9 ms) obtained at 1.5 T shows the osseous anatomy of the GT and LT.

ligament along the anterior edge of the supraspinatus tendon; and (5) a thin (1.5–2 mm) layer formed by the capsule of the joint, attaching to the greater tuberosity by the Sharpey fibers (**Fig. 3**). In the third layer, the interdigitation of the supraspinatus and infraspinatus tendons resulted in their apparent fusion.

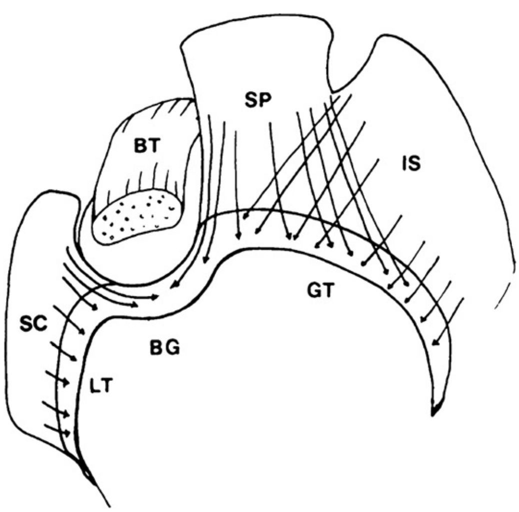

Fig. 2. The greater tuberosity (GT) receives fibers from the supraspinatus (SP) and infraspinatus (IS) tendons, showing an apparent interweaving of the fibers as they insert on the GT. The lesser tuberosity (LT) receives fibers from the subscapularis (SC) tendon. Also, fibers from the SP and SC tendons contribute to the floor of the bicipital groove (BG), which houses the long head of the biceps tendon (BT). (*From* Clark JM, Harryman DT. Tendons, ligaments, and capsule of the rotator cuff. Gross and microscopic anatomy. J Bone Joint Surg Am 1992;74:718; with permission.)

In a cadaveric study by Minagawa and colleagues,[3] a similar pattern of overlap of the supraspinatus and infraspinatus tendons was described. However, these investigators described the supraspinatus tendon as the only tendon inserting on the superior facet of the greater tuberosity, with some fibers inserting on the superior half of the middle facet. The infraspinatus tendon covered the posterior half of the supraspinatus tendon and attached to the entire length of the middle facet.[3] This type of interdigitation of the 2 tendons, which was described by Clark and Harryman[5] and subsequently by Minagawa and colleagues,[3] can be demonstrated on oblique sagittal images through the superior aspect of the cuff (**Fig. 4**).

Clark and Harryman[5] also described the existence of fibrous bands derived from the coracohumeral ligament that reinforced the superficial and deep portions of the supraspinatus and infraspinatus tendons near their greater tuberosity insertions. Regarding the relationship between the undersurface of the supraspinatus and infraspinatus tendons and the joint capsule, these structures adhered tightly near their humeral insertions. A 1-cm-wide thickening of the capsule derived from these fibrous bands of the coracohumeral ligament along the undersurface of the supraspinatus and infraspinatus tendons, located approximately 1.4 cm from the greater tuberosity footprint, was later termed the *rotator cable*, with the intervening portion of the cuff tendons designated as the *crescent*.[6] The muscles, rather than the tendons, of the infraspinatus and teres minor were inseparable just proximal to their myotendinous junctions. The teres minor demonstrated a muscular insertion approximately 2 cm below

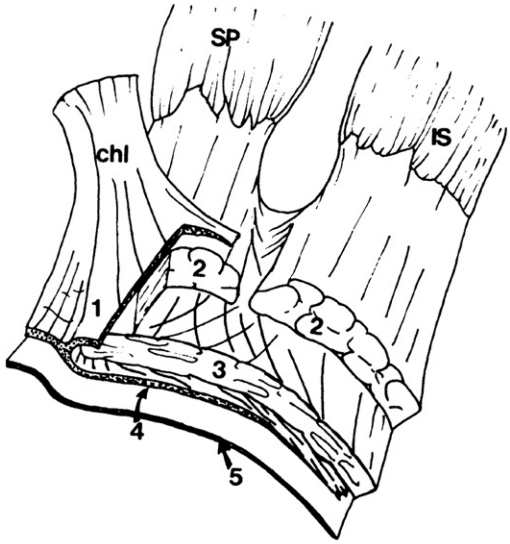

Fig. 3. The 5 histologic layers of the supraspinatus and infraspinatus tendons. Note that the coracohumeral ligament (CHL) forms an envelope around the tendons beginning at the anterior edge of the supraspinatus tendon (SP), forming layers 1 and 4. Layers 2 and 3 form the bulk of the tendon fibers, with the interweaving of the SP and infraspinatus (IS) tendons in layer 3. Layer 5, the deepest layer, is formed by the joint capsule. (*From* Clark JM, Harryman DT. Tendons, ligaments, and capsule of the rotator cuff. Gross and microscopic anatomy. J Bone Joint Surg Am 1992;74:723; with permission.)

its tendinous insertion on the greater tuberosity, a finding that can be demonstrated on MR images (**Fig. 5**).

More recently, the concept of separate tuberosity attachments of the rotator cuff tendons has been reexamined, specifically regarding the shared footprint of the supraspinatus and infraspinatus tendons. In a cadaveric study, Mochizuki and colleagues[7] revised the conventional understanding of this anatomy by demonstrating a relatively small, triangular, anteromedial footprint of the supraspinatus tendon at the superior facet and a comparatively large, trapezoidal footprint of the infraspinatus tendon occupying the anterolateral portion of the superior facet and the entire middle facet (**Fig. 6**). Again, this configuration can be depicted on oblique sagittal MR images (see **Fig. 4**). This arrangement led the investigators to conclude that the development of infraspinatus muscle atrophy in the setting of apparently isolated supraspinatus tendon tear may be related to the far anterior insertion of the infraspinatus tendon and that the infraspinatus muscle may be more biomechanically important during shoulder abduction than previously thought (**Fig. 7**).[7]

A possible related entity that has been recently described by Lunn and colleagues[8] is that of a novel lesion of the infraspinatus characterized by musculotendinous disruption, edema, and late fatty infiltration (**Fig. 8**). In their series of 19 patients, the investigators found full-thickness disruptions of the infraspinatus at the musculotendinous junction in 8 patients, within the tendon in 9 patients, and at an inconclusive site in 2 patients. These patients presented with acute pain, especially at night, with weakness of external rotation of the shoulder. This pathologic lesion was seen in middle-aged patients, with a mean age of 47.7 years, and more often in women than men. These investigators found a high incidence of accompanying rotator cuff pathology, including calcific tendinitis, tendinosis, and partial-thickness tears. Approximately 50% of their patients also reported a history of minor trauma, typically a fall on an outstretched arm. Only 1 of the 6 patients who underwent computed tomography (CT) arthrography demonstrated communication of contrast agent between the glenohumeral joint and the myotendinous junction of the infraspinatus.

Nimura and colleagues[9] further studied the contribution of the joint capsule and found that the capsule attached to the greater tuberosity beneath the supraspinatus, infraspinatus, and superior portion of the teres minor tendons. They described a biconcave area of attachment of the capsule medial to the rotator cuff tendons (**Fig. 9**). The thinnest portion of this capsular attachment was approximately 11 mm posterior to the anteriormost margin of the greater tuberosity, near the tapered posterior margin of the supraspinatus tendon, where it measured approximately 3.5 mm in width, which is in contrast to areas in which the capsular attachment was more robust, measuring as thick as 9 mm, located between the border of the infraspinatus and teres minor tendons. These investigators cited a study by Kim and colleagues,[10] which demonstrated that the most common site for degenerative rotator cuff tears was in an area 13 to 17 mm posterior to the biceps tendon. Thus, the thinnest capsular attachment on the greater tuberosity may be at risk for the development of these degenerative tears. Most partial-thickness tears of the rotator cuff tendons involve the articular side.[11–17] Earlier studies reported that most degenerative rotator cuff tendon tears affected the anterior portion of the supraspinatus tendon, with subsequent posterior propagation.[10] However, more recent studies have shown tears either isolated to or propagating from the infraspinatus tendon.[18,19] In a study by Goutallier and colleagues,[20] fatty degeneration of the infraspinatus muscle was demonstrated on preoperative CT

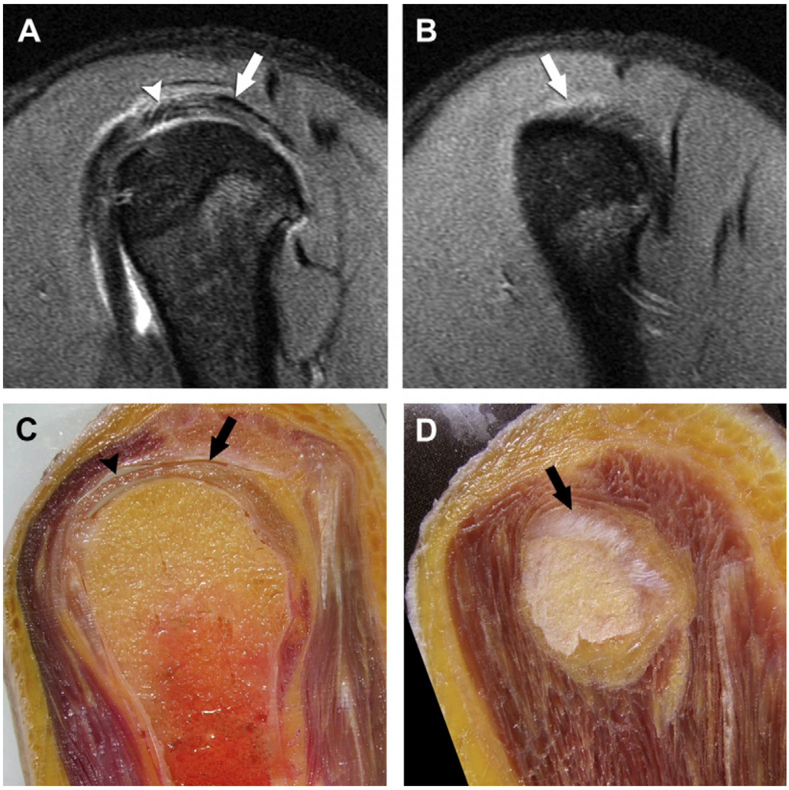

Fig. 4. Oblique sagittal proton density-weighted fat-suppressed images (repetition time [TR]/echo time [TE] = 3067/32 ms) obtained at 3 T at the level of the bicipital groove (*A*) and more laterally at the level of the greater tuberosity facets (*B*). Corresponding oblique sagittal cadaveric sections (*C*, *D*). The supraspinatus (*arrowhead*) and infraspinatus (*arrow*) tendons are identified separately on the more central images (*A*, *C*), whereas more peripherally, the fibers appear to interdigitate. In particular, the anterior fibers of the infraspinatus tendon appear to overlap those of the supraspinatus tendon and occupy the posterior half of the horizontal facet of the greater tuberosity (*B*, *D*).

scans, occurring in the context of large anterosuperior cuff tears that did not appear to involve the infraspinatus tendon (see **Fig. 7**).

The anatomy of the capsular attachments to the greater tuberosity and their relationship with degenerative cuff tears require that this discussion make reference to the bare area, initially described by DePalma[21] as a region along the posterior aspect of the humeral head between the insertion of the posterolateral capsule and overlying

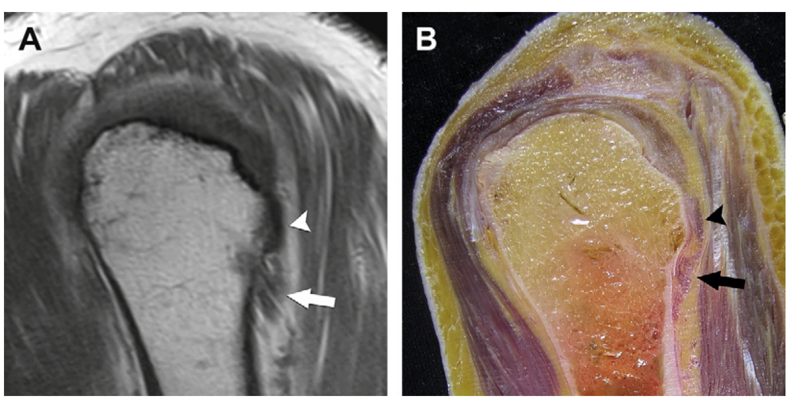

Fig. 5. (*A*) Oblique sagittal T1-weighted image (repetition time [TR]/echo time [TE] = 551/9 ms) obtained at 3 T and (*B*) oblique sagittal cadaveric section, showing the upper tendinous insertion of the teres minor (*arrowhead*) at the vertical facet of the greater tuberosity, with a muscular insertion (*arrow*) inferiorly at the surgical neck.

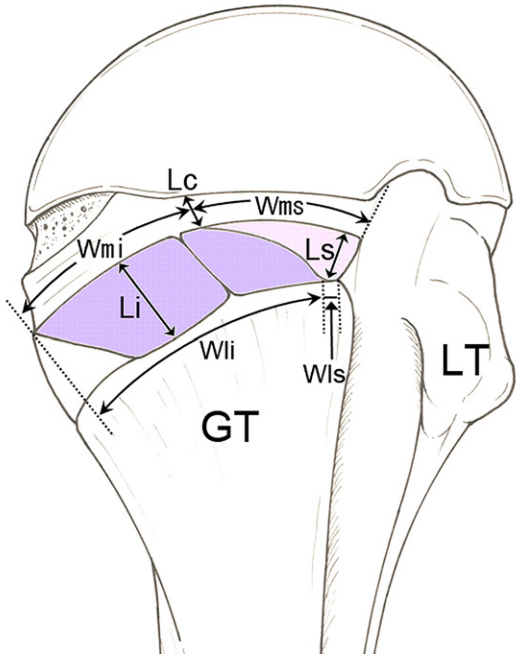

Fig. 6. The supraspinatus tendon footprint (*pink*) is depicted by a triangular area on the greater tuberosity (GT), whereas the footprint of the infraspinatus tendon (*purple*) is depicted by a larger trapezoidal area occupying the lateral portion of the horizontal facet. (*From* Mochizuki T, Sugaya H, Uomizu M, et al. Humeral insertion of the supraspinatus and infraspinatus. New anatomic findings regarding the footprint of the rotator cuff. J Bone Joint Surg Am 2008;90:966; with permission.)

synovial membrane and the articular surface of the humeral head. He reported that this sulcus increased in size from the third decade and theorized that retraction of the capsule and synovium was a phenomenon that occurred with age. The relationship between the bare area and the anatomy of the capsular attachment to the greater tuberosity described by Nimura remains to be elucidated. Perhaps there is gradual attrition of the capsular attachment with advancing age, resulting in an increasing bare area (**Fig. 10**).

Although not explicitly stated, the findings of Nimura and colleagues[9] may explain why degenerative rotator cuff tendon tears, even massive ones, appear to involve the teres minor tendon less often or not at all.[22–25] They found that the capsular attachment to the greater tuberosity was thickest at the posterior margin of the infraspinatus tendon, at the border with the teres minor tendon.[9] Also, the posterior extent of the capsular attachment was to the upper half of the teres minor tendon, whereas the lower half of the teres minor tendon had a muscular attachment on the surgical neck of the humerus without covering the articular capsule. These 2 anatomic findings may help contribute to a more structurally stable posteroinferior cuff.

The clinical significance of the footprint of the superior cuff has gained attention regarding the types of fixation that are used in the surgical repair of tendon tears. A conventional single-row suture anchor technique may not adequately reproduce

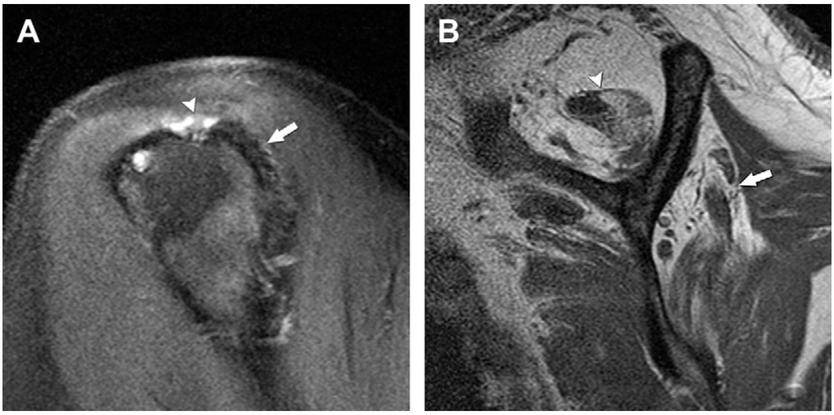

Fig. 7. Supraspinatus tendon footprint tear, with infraspinatus atrophy in a 78-year-old man with shoulder pain. (*A*) Oblique sagittal intermediate-weighted image (repetition time [TR]/echo time [TE] = 2800/56 ms) obtained at 3 T through the greater tuberosity facets demonstrates a full-thickness tear of the supraspinatus tendon (*arrowhead*), with a tendinotic but otherwise intact infraspinatus tendon (*arrow*). (*B*) Oblique sagittal T1-weighted image (TR/TE = 694/10 ms) at the level of the rotator cuff muscle bellies reveals both supraspinatus (*arrowhead*) and infraspinatus (*arrow*) muscle atrophy. (*Courtesy of* K. Chen, MD, San Diego, CA.)

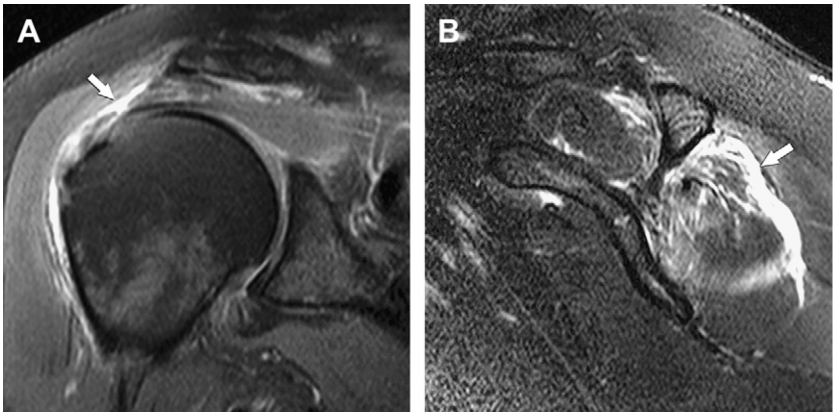

Fig. 8. Imaging appearance of the novel lesion of the infraspinatus muscle and tendon in a 61-year-old woman with worsening shoulder pain. (*A*) Oblique coronal proton density-weighted image (repetition time [TR]/echo time [TE] = 2300/29 ms) obtained at 1.5 T through the oblique facet of the greater tuberosity shows full-thickness tearing of the infraspinatus tendon near the footprint with minimal retraction of the torn tendon (*arrow*). (*B*) Oblique sagittal T2-weighted image (TR/TE = 3500/97 ms) at the level of the glenohumeral joint demonstrating significant intramuscular and extramuscular edema centered about the myotendinous junction of the infraspinatus (*arrow*). Edema is seen to a lesser degree about the supraspinatus muscle.

the anatomy of the native footprint and, in some cases, has been shown to be biomechanically inferior to a double-row suture anchor technique.[26,27] In recent literature reviews, the structural benefit of the double-row technique has been acknowledged; however, there seems to be little difference in the actual functional outcomes when comparing the benefits of single- and double-row procedures, except for a possible benefit of double-row techniques in the treatment of patients with massive cuff tears.[28,29] Further, prospective, randomized controlled trials with longer term follow-up are necessary before any useful conclusions regarding the functional outcomes of reconstructing the rotator cuff footprint are made.

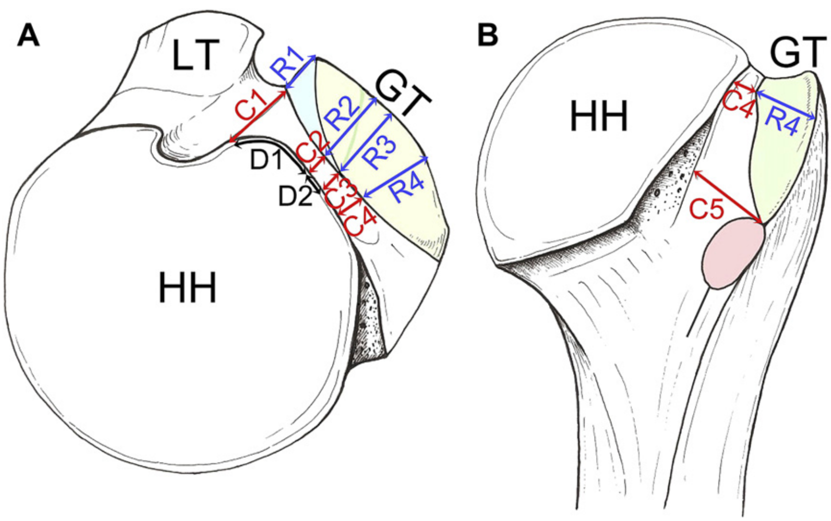

Fig. 9. Schematic illustration of the footprints in the greater tuberosity (GT) as seen from the superior (*A*) and posterior (*B*) aspects of the humerus. C1 to C5 represent the anterior to posterior extent of the capsular insertion deep to the rotator cuff tendons, with C2 representing the minimum width of the capsule. The footprint of the supraspinatus tendon spans R1 through R3, with C3 representing the width of the capsule at the posterior margin of the supraspinatus tendon. R4 represents the maximum width of the infraspinatus tendon footprint, whereas C5 represents the width of the capsular attachment at the posterior margin of the infraspinatus tendon footprint. LT, lesser tuberosity; HH, humeral head. (*From* Nimura A, Kato A, Yamaguchi K, et al. The superior capsule of the shoulder joint complements the insertion of the rotator cuff. J Shoulder Elbow Surg 2011 Aug 3. [Epub ahead of print]; with permission.)

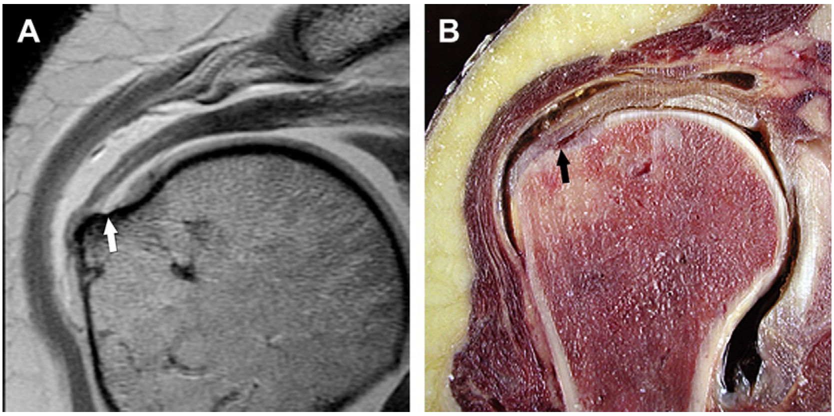

Fig. 10. The bare area of the humeral head in a cadaveric specimen. (*A*) Oblique coronal T1-weighted MR arthrogram (repetition time [TR]/echo time [TE] = 550/10 ms) obtained at 1.5 T shows the bare area representing the area of the footprint lateral to the edge of the articular cartilage that is not covered by tendon fibers (*arrow*). Note the absence of any torn, retracted articular-sided fibers along the undersurface of the tendon. (*B*) Corresponding oblique coronal cadaveric specimen showing the bare area (*arrow*).

FOOTPRINT OF THE SUBSCAPULARIS TENDON

Although a great deal of literature on the investigation of the superior cuff has been published, the anatomy of the subscapularis tendon footprint has garnered only recent attention. The subscapularis tendon may be injured because of falls on an outstretched arm, anterior glenohumeral joint dislocations, or subcoracoid impingement.[30] Tears of the subscapularis tendon were once thought to be uncommon, comprising 3.5% to 8% of rotator cuff tendon tears; however, with the advancement of arthroscopy, subscapularis tendon tears have been found to be much more common with a prevalence of up to 50% reported during arthroscopic rotator cuff repairs.[31] Clark and Harryman[5] demonstrated that the subscapularis had a muscular insertion approximately 2 cm below the lesser tuberosity at the surgical neck of the proximal humerus, similar to the insertion of the teres minor tendon.[5] This arrangement can also be depicted on MR images (**Fig. 11**). These investigators also reported a tendinous slip derived from the upper portion of the subscapularis tendon that passed under the biceps tendon to join with the fibers from the supraspinatus tendon, forming the floor of the biceps tendon sheath (**Fig. 12**). Similar to the supraspinatus tendon, the coracohumeral ligament sends fibers

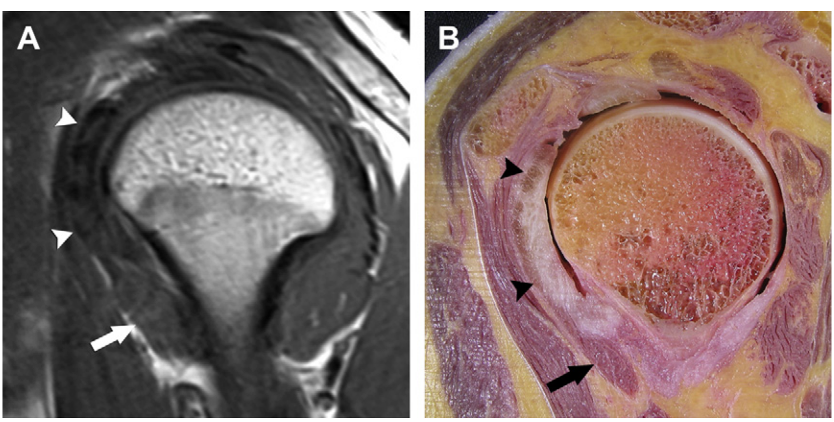

Fig. 11. (*A*) Oblique sagittal T1-weighted image (repetition time [TR]/echo time [TE] = 550/9 ms) obtained at 1.5 T showing that the attachment of the subscapularis muscle to the humerus comprises an upper tendinous insertion (*arrowheads*) in the lesser tuberosity and a muscular insertion inferiorly in the surgical neck (*arrow*). (*B*) Corresponding oblique sagittal cadaveric section demonstrating the same anatomy with an upper tendinous insertion (*arrowheads*) and a lower muscular insertion (*arrow*).

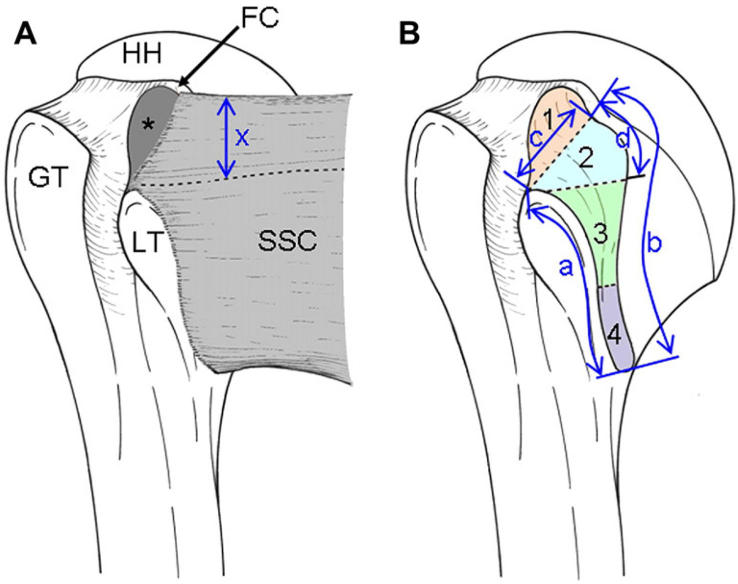

Fig. 12. Anatomic depiction showing the broader superior footprint of the subscapularis (SSC) tendon, with a relatively tapered inferior footprint and a thin muscular insertion below the lesser tuberosity (LT) in the surgical neck of the humerus. (*A*) The tendinous slip (*asterisk*) derived from the most cranial fibers of the intramuscular tendons (X) inserts on the fovea capitis (FC) above the LT. (*B*) Schematic representation of the footprint showing the tendinous slip (1), the insertion of the cranial-most fibers of the intramuscular tendons (2), the lower tendinous insertion (3), and the muscular insertion below the LT (4). GT, greater tuberosity; HH, humeral head. (*From* Arai R, Sugaya H, Mochizuki T, et al. Subscapularis tendon tear: an anatomic and clinical investigation. Arthroscopy 2008;24(9):997–1004; with permission.)

that reinforce the subscapularis tendon in the interval between the subscapularis and supraspinatus tendons. Thus, the subscapularis tendon plays a critical role in stabilizing the biceps tendon. The superior and middle glenohumeral ligaments also run deep to the subscapularis tendon from the medial to lateral edges of the tendon. The subscapularis tendon itself typically comprises 4 to 6 thick collagen bundles extending from the muscle belly medial to the lesser tuberosity.[5]

Since the investigations by Clark and Harryman,[5] more recent studies have attempted to characterize the subscapularis tendon footprint.[30,32–35] The shape of the footprint has been described as being akin to a human ear, a comma, and even the state of Nevada, with the common theme being that the subscapularis tendon has a broader superior insertion and tapered inferior insertion. Prior studies also document the presence of an inferior muscular insertion that occupies the lower third of the footprint, with the upper two-thirds being tendinous. One of these cadaveric studies[34] formally assessed the dimensions of the bare area, between the end of the articular cartilage and the most medial aspect of the subscapularis insertion, similar to that of the superior cuff. This bare area was of variable size, from as little as 2.9 mm to as much as 17.5 mm in width in a superior-inferior dimension. An anatomic and clinical study by Arai and colleagues[32] confirmed the presence of the upper tendinous slip described by Clark and Harryman,[5] located above the lesser tuberosity and attaching to the area designated as the fovea capitis of the humerus. Arai and colleagues[32] also recognized the important role of the most cranial part of the subscapularis tendon and its tendinous slip in the stability of the biceps tendon. They saw no unstable biceps tendons in the presence of an intact subscapularis tendon in their clinical cases. Conversely, in cases of an unstable biceps tendon, they found no intact subscapularis tendons.

SUMMARY

Knowledge of the precise anatomic characteristics of the footprints of the rotator cuff tendons continues to evolve. These anatomic characteristics are fundamental to the understanding of the pathogenesis of cuff failure, clinical manifestations of such failure, and development of the optimal treatment protocols. Regarding the greater tuberosity, recent literature suggests that the infraspinatus tendon may occupy a more substantial portion

of the anterior facet than previously thought and may explain the occurrence of infraspinatus muscle atrophy in the context of an apparently isolated supraspinatus tendon tear. The capsular contribution to the footprint may also be more substantial than previously described and may help maintain the integrity of the supraspinatus, infraspinatus, and teres minor tendons. A relatively narrow zone of the capsule in the region of the posterior fibers of the supraspinatus tendon may explain the subsequent development of degenerative tears in this location. Finally, the subscapularis tendon footprint plays an important role in the biceps tendon stability, by means of an upper tendinous slip derived from the cranial-most fibers of the intramuscular tendon. Subscapularis tendon tears are also more prevalent than previously described, their increasing discovery being likely related to the growing popularity of shoulder arthroscopy.

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